

Low-carbon cows: From microbial metabolism to the symbiotic planet

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Abstract

This article focuses on two projects – one at a large chemical company and the other at a small start-up – to intervene in the relations between cows and ruminal microbes to reduce bovine methane emissions. It describes these interventions as ‘symbiotic engineering’: a biopolitical technique targeting holobionts and becoming effective by working on interlaced sets of living things. Based on the analysis of these cases, the article elucidates a planetary symbiopolitics (Helmreich) that connects ‘molecular biopolitics’ (Rose) and ‘microbiopolitics’ (Paxson) to ‘bovine biopolitics’ (Lorimer, Driessen) and the politics of climate change. We critically investigate the spatial imaginaries of symbiotic engineering practices that single out the microbial realm as an Archimedean point to address planetary problems. This technoscientific vision resonates with the notion of the ‘symbiotic planet’ advanced by Lynn Margulis that depicts the Earth System, or Gaia, as a vast set of relations among living things down to the tiniest microbes. Margulis’ concept, as well as the ‘symbiotic view of life’ (Gilbert, Scott, Sapp) has been embraced in recent debates in STS as a way to think of multispecies worldings. The article contributes critically to these debates by showing what happens when the topology of the symbiotic Earth becomes the operating space for symbiotic engineering practices.

Keywords

symbiosis, Lynn Margulis, biopolitics, methane, microbes, climate change

In July 2020, Burger King started to test a new item on its menu: a low-carbon Whopper. No, not a low-carb burger to reduce your belly size, but a low-carbon burger to reduce your ecological footprint. The burger is made with beef from lemongrass-fed cows that

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Burger King claims burp out less methane because of their diet. Bovine methane emissions are one of the reasons why the consumption of beef, cheese and milk currently contributes more to global heating than the entirety of global air traffic. Burger King is not the only company trying to reduce bovine methane belches. A number of small biotechnology, clean technology, and agricultural companies, as well as big chemical conglomerates, are trying to turn this problem into a profitable business by developing and marketing methane inhibitors sourced from seaweed, garlic and citrus extracts, or designed chemical compounds. Given increasing consumer demand for sustainable food and governmental initiatives to reduce emissions from the agricultural sector, involved players believe the cow belch business to be a 1–2 billion-Euro market (DSM, 2020: 82). Companies promote visions of a ‘clean cow’ or ‘climate-friendly cow’. However, the inhibitors do not primarily target the cow but rather the communities of microbes residing in the rumen – one of the cow’s four stomachs. Cows and other ruminants, like goats or sheep, live in symbiosis with myriad microbes that help them to digest grass but, in the process, also produce methane. Therefore, methane inhibition aims to intervene in symbiotic relations between the host animal and its microbes. It alters a holobiont: ‘an organism plus its persistent communities of symbionts’ (Gilbert, 2017: M73).

In this article we analyze current attempts to reduce methane emissions from cow belches through interventions in symbiotic relations between ruminants and microbes. We focus on the science and business of inhibitor development at two European-based companies – the chemical conglomerate DSM and the start-up Mootral.¹ Conceptually, we seek to contribute to STS debates on microbiology (Lorimer, 2017; Paxson and Helmreich, 2014; Schrader, 2010), symbiosis (Haraway, 2016; Tsing, 2015), and Gaia (Hird, 2010; Latour, 2017; Stengers, 2015) by showing how symbiotic relations between microbes and host animals became a target for technoscientific intervention.

We understand such interventions as ‘symbiotic engineering’: techniques that manipulate symbiotic relationships to repair or optimize life processes and ecosystems. Symbiotic engineering often requires elaborate biotechnological measures but also everyday practices such as eating probiotics to improve gut health (Folkers and Opitz, 2020: 250–253). In contrast to other biotechnological interventions like genetic engineering, it does not address individual bodies but rather holobionts, and more generally the relation between interlaced sets of living things. The type of symbiotic engineering discussed here does, however, share similarities with geoengineering through the deliberate attempt to manipulate geochemical cycles to fight global warming (Yusoff, 2013). The modification of the microbial metabolism in the rumen likewise seeks to mitigate climate change and counter a rift in the planetary ‘carbon metabolism’ (Clark and York, 2005). It therefore represents a mundane or ‘everyday practice of geoengineering’ (Ormond, 2020: 136). Symbiotic engineering thus claims to target the microbial root of planetary troubles. It aims at planetary conditions, but it acts on a microbial, and, as we will see, even molecular level.

We argue that symbiotic engineering harbors a form of biopolitics, or rather ‘symbiopolitics, the governance of relations of entangled living things’ (Helmreich, 2009: 15). Lorimer (2020: 81–107) has elaborated on this concept in his work on probiotic techniques that ‘use life to manage life’; according to him, symbiopolitics works through the strategic introduction of keystone species to restore ecological relations. Though our

take on symbiopolitics is sympathetic to Lorimer's framing, we show that symbiotic engineering, which we take to be the crucial technology of symbiopolitics, is not necessarily probiotic but also involves a series of other (i.e. molecular) strategies to alter symbiotic relations. Our focus on symbiotic engineering stresses that symbiopolitics comes to operate on and connect different scales and types of biopolitics. In our cases, we analyze a form of planetary symbiopolitics that connects 'molecular biopolitics' (Rose, 2007), 'microbiopolitics' (Ironstone, 2019; Paxson, 2012b), 'bovine biopolitics' (Lorimer and Driessen, 2013; also Bloomfield and Doolin, 2011; Cooper, 2017; McGregor and Houston, 2018; Orland, 2004) and the politics of climate change (Jasanoff and Martello, 2004; Miller and Edwards, 2001). We thus show how symbiopolitics operates on, or rather between, multiple scales and the three poles of biopolitics: the body (cows), the population (microbes), and the (planetary) environment.²

Some scholars in STS and the environmental humanities have recently embraced the 'symbiotic view of life' (Gilbert et al., 2012), promoted in parts of the life sciences to rethink naturecultures in an age of ecological crisis (Tsing et al., 2017). We approach symbiosis from a different angle, not assimilating symbiosis thinking into our conceptual repertoire but showing how it operates in biopolitical techniques. We seek to tease out the resonances and dissonances between the spatial operating mode of symbiotic engineering and approaches to 'the global' or 'the planetary' in STS. That 'the global' is an effect of local practices, rather than a giant stage where action unfolds, is a core tenet of STS research on globalization (Knorr-Cetina and Bruegger, 2002; Law, 2004; Tellmann et al., 2012). At the interface of microbiology and Gaia theory (Margulis, 1999), a similar idea has taken hold in the life and earth sciences. Planet Earth is not a giant sphere (Sloterdijk, 1999), nor a total environment encompassing all life forms. Rather, crucial features and regularities of the Earth System are the effects of countless conspiring life forms. Microbes, in particular, are of utmost importance for planetary ecologies from the oceans to the atmosphere. As discussions on Gaia and the Anthropocene proliferate, STS scholars have turned to these biological insights with great fascination (Hird, 2010; Latour, 2017) and have begun to adopt these theories.

Approaching symbiosis from the vantage point of symbiotic engineering is not intended to discredit the valuable discussions on symbiosis in STS; symbiotic thinking can certainly enrich these debates. However, the symbiotic turn in STS and social and cultural theory more broadly (Clarke, 2020; Hörl, 2018), has produced an 'increasingly normative body of ecologized social theory' (Lorimer, 2020: 12). These, however, tend to lose sight of the power relations that go along with contemporary symbiopolitics. By recruiting symbiosis thinking as a welcome ally against reductionism in biological research and modernist ways to dominate nature, these approaches mostly fail to see how symbiosis has become a target for biotechnological projects and capitalist ventures. We thus call for treating symbiosis not only as a tool but also as an object of STS research.

The symbiotic view of life and the Earth

The biological concept of symbiosis, which describes mutualistic, commensal, or parasitic relations among organisms, was introduced in the late 19th century (Sapp, 1994; Sprenger, 2020). The elevation of symbiosis thinking from a somewhat marginal subject

matter of the life sciences to a new biological paradigm is, however, a more recent development. Anticipated by Margulis in the 1960s, in recent decades increasing numbers of biologists and analysts of biology have promoted symbiosis thinking as a postmodern alternative to the ‘modern synthesis’ between evolutionary theory and genetics that dominated the 20th century (McFall-Ngai, 2017). By declaring that ‘we are all lichens’, a programmatic paper by the biologists/historians/philosophers Scott Gilbert, Jan Sapp and Alfred Gilbert et al. (2012) introduces the ‘symbiotic view of life’, maintaining that symbiosis is not just a biological curiosity but the normal, almost universal way in which life operates. Though far from uncontested, the ‘symbiotic view’ opens up – among other things – new perspectives on environmental relations.

In his essay ‘the living and its milieu’, Georges Canguilhem (2008: 98–120) sketched the emergence of biological notions of the environment – from 19th-century notions, according to which the environment determines the organism, to their reversal in Jakob von Uexküll’s work, in which the organism actively selects the parts of its surrounding that matter to it as an environment. The symbiotic view goes beyond both deterministic and constructivist views of the environment because one can no longer assume the separateness of ‘the living and its milieu’. ‘What happens’, asks Donna Haraway (2016: 30) with the symbiotic view in mind, ‘when organisms plus environment can hardly be remembered’? Symbiosis thinking, thus, reckons with complexly folded ecologies of, as Anna Tsing and colleagues describe, ‘bodies tumbled into bodies’ (Gan et al., 2017). Entangled in a symbiotic web of relations, each organism only has an environment to the extent that it is an environment for others (Folkers, 2017: 373; Folkers and Opitz, 2020: 243–245). Again, Lynn Margulis is a key figure in the rethinking of environmental relations in symbiotic terms (Sprenger, 2020). Her theory of endosymbiosis drew attention to the ways in which organisms seek refuge in other organisms and how they, in turn, environ their host from within.

Gaia theory, developed in collaboration with James Lovelock, extends Margulis’s thinking of symbiotic topologies to the planetary. The theory argues that the biosphere regulates the atmospheric conditions that make life possible (Lovelock and Margulis, 1974). Life does not just passively adapt to its environment. It actively shapes and regulates it. This not only holds true for the biosphere as a whole, but also the minute interactions among symbiotically entangled critters. Microbial communities help to keep their host/environment in favorable conditions and, at least most of the time, secure the survival of the holobiont. Later, Margulis introduced the notion of the ‘symbiotic planet’ and – inspired by Greg Hinkle, a PhD student of hers – declared: ‘Gaia is just symbiosis seen from space: all the organisms are touching because all are bathed in the same air and the same flowing water’ (Margulis, 1999: 2).

Curiously, the interaction between the metabolism of ruminants and the atmosphere served as a paradigmatic case for figuring out the folded environmental relations of the symbiotic planet. Here, the cow frequently figures as an ‘obvious example of ... a holobiont’ (Gilbert, 2017: M73).³ Thanks to its microbial partners, the cow can use otherwise indigestible fibers. In turn, the cow provides the microbes with nutrients and a safe, warm and anaerobic environment. For theories of the ‘symbiotic planet’ (Margulis, 1999), the bovine holobiont appears a ‘four-legged methane tank’ (Sagan, 2013: 28). When Gaia theory emerged in the early 1970s, the relatively high concentration

of methane in the Earth's atmosphere posed an intricate puzzle. Since methane (CH₄) oxidizes rapidly and turns into carbon dioxide (CO₂) it should, given the laws of chemistry, have long disappeared throughout the history of the Earth. So why is there still methane in the atmosphere? Troubled with this question, Lovelock turned to Margulis (1999), who later (p. 117) recalled: 'Methane gas is produced by bacteria, mainly the methanogens that live in waterlogged soil or in cattle rumen. ... Methane is released into the air through the mouths of calves, bulls, and cows. ... Lovelock realized that atmospheric methane concentrations must therefore be produced by life'. Methane thus became an indicator of planetary life. In their seminal article on the Gaia hypothesis, Lovelock and Margulis (1974) showed this by comparing the methane concentration of the Earth with Mars and Venus. In his book *The Cosmic Connection*, Carl Sagan (1973: 121) – Margulis's ex-husband – speculated that aliens might one day detect life on Earth because of cow farts (actually, it's mostly belches).

In fact, life on Earth ... could be detectable with a small telescope and an infrared spectrometer from the vantage point of Mars. The Martians, if any, could easily observe, at a wavelength of 3.33 microns in the infrared, a strong absorption feature that straightforward analysis would reveal to be due to one part per million of methane in the terrestrial atmosphere. ... This means that bovine flatulence ... is detectable over interplanetary distances.'

In Gaia theory, methane molecules become 'interscalar vehicles' (Hecht, 2018) that allow scientists to track the connections of the microbial and the (inter)planetary through all the symbiotically entangled sites it passes on its journey. The rumen – the cow's stomach where the microbial magic happens – is thus not only a critical passage point for the metabolism of cattle, but also the metabolism of the symbiotic planet, the exchange between biosphere and atmosphere.

'[M]icrobes do the work of grass digestion. ... Indeed, the cellulose-degrading microbes, in a very real sense, are the cow. ... One of the gaseous products of grass digestion is methane. ... Bovine methane is part of the reason that Earth's air is a highly unstable chemical mixture. ... The long-term unstable gas systems of the atmosphere result from incessant microbial life. (Margulis, 1999: 122)

If it is true that the atmosphere is an 'essential part of the biosphere as [is] the shell to a snail or the fur to a mink' (Lovelock and Margulis, 1974: 6), then the rumen is just another membrane within the folded topology of Gaia.

The symbiotic view has also inspired approaches to rethink the Earth in STS. Myra Hird (2010) has mobilized Margulis' theories for an alternative understanding of the Earth that stresses the importance of microbes for planetary life and thus radically decenters the human. In a similar vein, Isabelle Stengers et al. (2008: 7) has maintained that 'bacteria ... are on Gaia's scale and like her', suggesting that Gaia isn't to be found in the very large but in the very small. Bruce Clarke (2020: 10) echoes this very point: 'The microcosm is the most planetary and arguably the most consequential component of the biosphere'. In his engagement with Gaia theory, Bruno Latour (2017: 99, 101, 104–105) explicitly acknowledges Margulis's role in counteracting what he identifies as the biggest problem in Lovelock's take on Gaia: The treatment of the Earth as a

thermostat-like totality. Margulis' emphasis on symbiosis and the role of microbes in the regulation of the planet amounts to a micro-foundation of Gaia theory. Although she frequently refers to the notion of autopoiesis, by thinking with Margulis it becomes possible to depict Gaia as an effect of 'symptoiesis' (Haraway, 2016: 58–98), a multispecies worlding and becoming-with. The regulatory features of the Earth become visible as the emergent effect of distributed and intrinsically connected agents that do not share a total environment but provide environments for each other.

[F]or Lovelock, and even more clearly for Lynn Margulis, *there is no longer any environment* to which one might adapt. ... The inside and outside of all borders are subverted ... because the interaction between neighbours [Margulis would probably say roommates] ... could be called *waves of action*, which respect no borders, and even more importantly, never respect any fixed scale. (Latour, 2017: 100f.)

It is tempting to adopt the theory of the symbiotic planet to reflect on contemporary ecological problems. However, in what follows we slightly shift the analytical focus and show how this spatial vision reappears in technoscientific responses to these problems. We examine what happens when the topology of the symbiotic Earth becomes the operating space of biopolitical interventions that depict symbiotic entanglements between living things as a site to engineer the Earth System.

Microbial climate politics: Connecting the rumen to the atmosphere

Methane emissions from ruminants, especially cattle, have become an important and rapidly emerging problem space for climate mitigation (Ormond, 2020). About 14.5% of global greenhouse gases (GHG) stem from livestock farming. Cattle account for 65% of these emissions and enteric fermentation makes up 39% of the total livestock emissions, so about 5.7% of total global emissions (Gerber et al., 2013: xii). The numbers suggest that while the emissions per cow are higher in the highly productive cattle industries in Europe and the US, their emission intensity (the emissions per unit of beef or milk) is significantly lower compared to other parts of the world. International organizations like the FAO (FAO and NZAGRC, 2019), therefore, promote attempts to reduce the emissions intensity of ruminants in so-called 'low productivity systems' through techniques such as 'herd management, animal health and husbandry practices' (Gerber et al., 2013: 42). According to the FAO, this would not only decrease methane emissions but could also contribute to food security. Less methane means more milk and meat because cows lose between 2% and 12% of their energy through burped methane (Johnson and Johnson, 1995).

Attempts to decrease emission intensity represent a new form of 'bovine biopolitics'⁴ that connects cattle to the climate. The focus on emissions intensity seeks to align the new ideal of the low-carbon hoofprint cow to the traditional ideal of agricultural bovine biopolitics: the 'efficient accumulator' (Lorimer and Driessen, 2013: 252). Bovine climate politics, thus, aligns with modernist and (neo)colonial agricultural project(ions) that regard traditional forms of agriculture, especially in poor countries, as overly

wasteful and in need of improvement (Goldstein, 2018: 32–36). Yet since in Europe and North America the ‘turbo cow’ (Orland, 2004) is already the norm in livestock farming, the repertoire of techniques to lower their emission intensity by boosting efficiency has already been largely exhausted. This explains why the symbiotic processes within the ruminal microbiome have become a new frontier for reducing enteric methane emissions in high-productivity systems (Beauchemin et al., 2020). In contrast to the approach promoted by the FAO, this strategy resorts less to forms of ‘pastoral power’, which focus on managing cattle herds, and instead combines bovine biopolitics with techniques of microbiopolitics: ‘means of ... regulation carried out through control of microbial life’ (Paxson, 2012a: 160).

Efforts to turn the rumen into a site of climate mitigation and agricultural improvement became possible through recent advances in the understanding of microbial processes involved in the metabolism of ruminants. As in other branches of microbiology (Helmreich, 2009: 51–63; McFall-Ngai, 2017: 52–57), genomics and bioinformatics critically contributed to making the microbial species and processes in the digestive tracts of ruminants legible. In addition, the so-called rumen-simulation technique (RUSITEC) (Czerkawski and Breckenridge, 1977), an apparatus composed of a series of fermentation vessels, makes it possible to run experiments on ruminal metabolism outside of the cow in a controllable laboratory environment, using rumen fluid as a starter. This avoids the practice of cannulation, where a permanent hole is cut into the animal to extract samples directly from the cow’s rumen. These scientific devices enabled biologists to, sometimes quite literally, open the black box of bovine digestion and to reconfigure the ruminal metabolism – a symbiotic process involving thousands of microbial species. Therefore, it has been shown that a cow not only lives in symbiosis with its ruminal microbiome, but the different microbial species in the rumen – bacteria, protozoa, fungi, archaea (Tapio et al., 2017) – also live in complex symbiotic relationships with each other. Microbiologists describe the rumen as an intricate ecosystem whose complexity poses challenges and offers opportunities for attempts to modify it. The challenge is to intervene in microbial relations without damaging their vital functions, because ruminants depend on the bacterial fermentation of celluloses. Even the generation of methane by the archaea has an important function: It removes one of the by-products of the fermentation process – hydrogen – by combining it with carbon dioxide to make methane (Hook et al., 2010). Methanogenesis is a hydrogen sink. So, even though they contribute to wasting the atmosphere, methanogenic archaea are a waste disposal unit in the rumen. Therefore, disrupting the fermentation process or inhibiting the methanogenic hydrogen removal too much would be detrimental to the cow. Luckily, at least for the cow, the ruminal microbiome has a high degree of ‘functional redundancy’ (Henderson et al., 2015: 7) and resilience (Brade and Wimmers, 2016: 3–4) and recovers quickly from disturbances.

For scientists involved, this means that many attempts to intervene in the ruminal biome are bound to fail. Scientists have unsuccessfully tried: to transfer the microbiome of macropods – that is, kangaroos – to ruminants, because the former are known to emit less methane (Wilson and Edwards, 2008); to reprogram the microbiome in the early life of the animal (Yáñez-Ruiz et al., 2015); to reduce the amount of hydrogen in the rumen by targeting protozoa (Tapio et al., 2017: 4); and to colonize the rumen with acetogen

bacteria able to metabolize methane into nutrients (Interview). The list of efforts goes on and on. Still, the scientists we interviewed were very confident that the diversity of microbial species and the entangled trophic relations among them provide plentiful still-unknown ‘levers’ to pull and ‘screws’ (Interview) to turn. Despite the many setbacks, the common perception of the cow’s ruminal metabolism as a field of unexplored opportunity attracts more and more research projects and scientists, including animal and agricultural scientists, chemists, molecular biologists and microbiologists, seeking to decrease methane emissions (Beauchemin et al., 2020).

Carbon, cattle, capital: The bovine burp business

We turn to two projects in the bovine burp business: the ‘clean cow’ project at the chemical conglomerate DSM and the small biotech start-up Mootral. Both projects are typical for the current wave of methane reducing approaches that focus mainly on the cow-climate nexus (Cooper, 2017; Ormond, 2020). This contrasts with earlier attempts to reduce bovine methane emissions – some of which date back forty or fifty years (Beauchemin et al., 2020) – that were preoccupied with increasing the efficiency of the cow’s energy metabolism for higher agricultural yield. This does not, of course, mean that the involved companies do not care about economic yield. In fact, both try to turn low-carbon innovation into a profitable business venture and give one of the oldest forms of biocapital – livestock farming⁵ – a new twist.

Project clean cow: Applying a molecular vision to a planetary problem

The clean cow project started at DSM nutritional products (formerly Roche vitamin) in 2007 as an effort to focus more attention on sustainable innovation. The team of researchers at DSM had backgrounds in biochemistry but almost no particular knowledge of bovine metabolism prior to working on the project. They started to look at existing research on the topic and were – as the head of the team told us – baffled about the absence of the ‘molecular vision’ (Interview) in existing approaches. Whereas veterinary scientists mostly test how different feeding regimes affect methane production, the biochemist at DSM changed the focus and scale of this approach by targeting the agents and molecular structures they deemed responsible for regulating the bovine metabolism. They quickly recognized that one enzyme (methyl-coenzyme M reductase, MCR) might be the correct target because all methanogens need it to synthesize carbon dioxide and hydrogen into methane. Adopting an approach common in rational drug design, the clean cow researchers ran a series of molecular docking studies on a computer that simulated which molecules are likely to be able to block the active site of the enzyme. It turned out that the most promising candidate for inhibiting methanogenesis was the molecule 3-nitrooxypropanol (3NOP). The inhibitor was, therefore, designed in silico before being tested in vitro and in vivo.

Since then, more than thirty scientific studies, often conducted in collaboration between DSM researchers and scientists from public research institutions, have shown how 3NOP works on the molecular level (Duin et al., 2016) and how it affects the cows on the farm (Hristov et al., 2015). The compound promises to reduce methane emissions

by 30% without known negative side effects for the animal's health or its products. In fact, studies suggest that cows may even get fatter and produce more milk when given the inhibitor (Hristov et al., 2015) because they can use some of the valuable energy they otherwise just burp out. Researchers attribute this to the targeted approach that only inhibits methanogenesis at the 'bottom of the trophic chain' (Duin et al., 2016: 6172), leaving all the other metabolic processes in the rumen intact. The idea is that the inhibitor cuts through the complexity of ruminal symbiosis by targeting a specific enzyme.

The name of the project – clean cow – alludes to the pretences of the traditional fossil industries like 'clean cars' or 'clean coal'. Further, it obviously has an eye out for 'clean meat', meat that is grown *in vitro* and promises to disrupt the food industry (Gertenbach et al., 2021; Jönsson, 2016; Sexton et al., 2019). However, DSM's immediate target audience – once their compound is approved by the regulatory authorities – will not be distinguished 'climatarians' who want to enjoy their artisanal cheese without heating up the planet, but conservative cattle farmers under increasing pressure to produce more beef and milk at a low price. The promise of productivity gains through methane inhibition, the 'efficient' and not just the 'clean' cow, is thus a crucial selling point for DSM. Officials argue that the inhibitor will pay for itself considering the farmers would have to give their cows less fodder (Schilliger, 2017). Similar to the FAO programs, DSM seeks to align the modern ideals of agriculture – efficiency – with those of climate governance – hoofprint reduction. At DSM, this alignment is, of course, intended to increase the value of their product. The equivalence of energy efficiency and reduced methane production rooted in the biochemistry of the rumen creates both an economic and an ethical 'biovalue' (Waldby, 2002). It smoothly translates into an economic selling point – the clean/efficient cow – and a bold promise: The compound, DSM (2019) claims, can not only fight global warming, but also increase food security by increasing agricultural production.

Curiously, DSM stands for Dutch State Mines and was founded in 1902 as a government-run coal mining company that until recently very much embodied the values and business models of 'fossil modernity' (Folkers, 2021). During the 20th century, DSM turned into a large chemical company specializing in chemical fertilizers and petrochemicals like plastic (Van Rooij, 2007). In a way, 3NOP also functions like fertilizer for the cow – the only difference is that it works by reducing (renewable) energy loss and not by adding chemical energy from finite resources. DSM's endeavors promise to address the problems not least caused by their traditional 'necrocapitalist' (Helmreich, 2009: 126) business model based on fossil feedstocks. They set out to transcend the ecological 'limits of growth' (Cooper, 2008: 15–50) that not only fossil and chemical industries but increasingly also industrial agriculture have to wrestle with (Guthman, 2019). Inhibiting methanogenesis literally means internalizing the externalities of livestock farming. It keeps the molecules that cows would otherwise belch out as greenhouse gas inside the digestive tract, where they can be used as energy to increase milk and beef yield. Symbiotic engineering seeks to put waste to work. The rumen, thus, not only becomes a novel site of climate mitigation but also turns into a new frontier within the capitalist 'web of life' (Moore, 2015). Capital no longer just 'appropriates' the 'work/energy' of microbes as a free gift of nature, but actively recruits an optimal microbial workforce to ensure a more efficient 'exploitation' of their symbiotic labor.⁶

Mootral: Making microbiome changes scalable

Among DSM's competitors is a small start-up called Mootral (pronounced like 'neutral' but with 'moo'). Their product, also called Mootral, is a garlic and citrus-based feed supplement that promises to reduce methane emissions by up to 38%. The development of the methane inhibitor grew out of research at Neem, a small Welsh biotech company. Neem specializes in developing drugs against antibiotic-resistant bacteria by experimenting with extracts from natural substances like garlic that have proved to target methanogens. After the Paris Agreement opened new political and economic horizons for low-carbon innovation, officials at Neem's holding company decided to launch Mootral as a separate company and to push research for a methane inhibitor further (Interview).

Mootral is keen on emphasizing the naturalness of its product. Researchers there stress the long tradition of harnessing the antimicrobial properties of garlic in alternative and traditional medicine. Yet, the secret of the supplement tested *in vitro* (Eger et al., 2018) and *in vivo* (Roque et al., 2019) is, they claim, the combination of allicin (obtained from garlic) inhibiting methanogens, and flavonoids from citrus extracts promoting bacteria vital for ruminal fermentation. In their advertising, Mootral takes up the popular distinction between 'good bacteria' helping the cow to digest food and 'bad microbes' sucking energy and emitting methane – although interviewed scientists were keen to point out that methanogens are not actually 'bad'. Still, whereas scientists and DSM researchers describe the chemical compound 3-NOP as a 'warhead' (Duin et al., 2016: 6175) that very specifically targets methanogens, Mootral scientists claim that they pursue a mode of methane inhibition geared toward changing the entire microbial community structure with antimicrobial as well as prebiotic agents. As a Mootral researcher explained to us: 'We inhibit one population and promote another population to have a mutation in the microbiome, to reduce methane production ... without destroying the overall assemblage' (Interview, authors' translation). While the clean cow project at DSM represents a form of 'molecular biopolitics' (Rose, 2007),⁷ Mootral's approach fits what Lorimer (2020) describes as a 'probiotic turn' in biopolitics that seek to re-engineer and restore ecologies.

Mootral is currently trying to introduce its feed supplement to the market. In contrast to other biotech start-ups, Mootral's goal is not just to sell the company or a patent, they are committed to penetrating the market and thus make money by selling a commodity – Mootral, the feed supplement. However, since it is a start-up and has significant expenditures, especially for R&D, it also has to sell parts of the company as assets to investors (on assets see Birch, 2017). To receive funding, Mootral must convince venture capitalists, infamously more focused on future potential than in present profitability, of its ability to grow and expand so that the company can generate cash flows in the future. A Mootral business official told us that their investors are especially interested in 'scalability':

At the moment, they are interested in scale-out. They say: 'Hey, you have this product. Yes, we know that the product is not 100 percent ready, ... but how many cows, how many countries, how many businesses would use and buy Mootral?' That's the interesting point. Some investors don't want to see profits from a start-up in the beginning, they want to see potential for increased revenues, scalability and then see how it develops. (Interview, authors' translation)

In the investor's gaze, future economic potential depends on scalability, the ability to expand and thus to find a solution for the planetary problem of climate change. The venture capitalists are 'invested' in a vision of scalability that, as Tsing (2012) shows, has been at the core of modernist visions of progress and/as growth at least since the beginning of the colonial plantation economy. However, ecological complexities and symbiotic entanglements often resist attempts to scale up.⁸ 'Making projects scalable takes a lot of work' (Tsing, 2012: 507). This definitely applies to attempts to scale up methane-inhibiting feed supplements that not only encounter the complex symbiotic entanglements within the rumen but also a myriad of forms of cow breeds, farm systems and feeding regimes around the world. The economic desire for scalability brings forth a scientific challenge as a Mootral scientist explained:

You find different conditions on almost every farm. So, of course, there is a lot of standardization in dairy farming. But every company is somehow unique in its application. ... And beef cattle... this is something else again Mootral has to work under a wide variety of conditions, humidity, temperature etc. There are still many trials necessary ... to prove the basic fact that it works breadthwise. (Interview, authors' translation)

Scientists must prove that the inhibitor can work in every kind of farm system, for every kind of cattle breed and in every ruminal ecology. At the very least, they have to find 'articulations between scalable and non-scalable elements' (Tsing, 2012: 515). Accordingly, research activities at Mootral currently concentrate on trials that test the inhibitor, adapt it to different farm systems and translate the findings from lab studies to farm conditions. This is a huge scientific and financial challenge for a small start-up. Although the clean cow project at DSM receives its funding from the R&D budget of a multinational chemical company, they faced the same scientific challenge. Once they developed the inhibitor *in silico* and tested it *in vitro*, they started to exclusively concentrate on *in vivo* trials to figure out how it performs under different conditions. The sheer number of necessary research trials came as a surprise to the molecular biologists at DSM, who suddenly had to collaborate with veterinary scientists.

I was also surprised by this. I told you, I am not a farmer And I thought: Man! In the world where I come from, you make two, three trials. If they all show the same result, you say: 'done!' (Interview, authors' translation)

DSM scientists had to leave their scientific 'world' made up of computer simulations, molecular structures, and microbiological lab equipment. They were forced to enter the much messier world of farm animals and burp measurement as the scientific promise of replicability came up against the reality of multiple ruminal and agricultural ecologies. The economic promise of scalability, therefore, depends on the scientific aspiration to show that lab findings are applicable to the world outside of it (Latour, 1988). The imperative to make symbiotic engineering solutions scalable changes the symbiotic entanglements. Inspired by Margulis's (1999: 6) notion of 'sympiogenesis', Haraway (2016: 58–98) emphasized the generative capacities of 'sympoiesis' as a form of 'becoming-with'.⁹ Symbiotic assemblages change by making new connections, meaning they can

only expand by constantly evolving. Scalability, however, requires expansion without change (Tsing, 2012). Symbiotic engineering, thus, seeks to modify symbiotic relations while also trying to arrest their potential for spontaneous transformation.

Measuring and marketing methane emissions

The effort to make global Mootral and the symbiotic modification it affects is informed and incited by the prospect of the catastrophic planetary future as a result of climate change. Methane inhibition will likely only become big business if governments start putting a price on agricultural emissions. Until now, however, no country has introduced a tax on cow burps, nor do emissions trading schemes consistently include agriculture. Accordingly, the prospect of future climate regulations has a huge impact on the expectation of potential value for companies like Mootral; a fact that their business officials pointed out. ‘They [investors] know that climate change is a huge problem and that governments will increase pressure’ (Interview, author’s translation). The ‘conjunction of promissory biocapitalist futures’ (Rajan, 2006: 107–137) relies on a gloomy ecological future that the supplement may help to pre-empt or at least mitigate.

In the absence of politically orchestrated infrastructures for measuring and pricing methane emissions, Mootral launched what they call a ‘cow credit project’. They devised the first ‘methodology for the reduction of enteric methane emissions from ruminants’ (Zoupanidou, 2019) accredited by the ‘Verified Carbon Standard’ organization Verra. Farmers and/or companies willing to use Mootral, and to take on the quite laborious task of measuring cow burps, can now earn verified carbon credits, or ‘cow credits’, and sell them to buyers – companies or individuals – interested in voluntarily compensating their emissions. The carbon price in these voluntary markets is currently too low to compensate for the expenses of the feed supplement and the measuring effort. However, the verification of the carbon numbers is not only an ‘obligatory passage point’ (Callon, 1984) for entering carbon markets but also works as an infrastructure of consumer transparency by allowing farmers and companies to make their carbon numbers public. In fact, the promise of transparency and verified carbon reductions was the main incentive for Mootral’s flagship farm to adopt the supplement. The Brades farm in the north of England currently sells a ‘barista milk’ to coffee shops in London (see Mootral, 2022). The farm hopes that by adopting Mootral, it will become more competitive with plant-based milk companies that advertise their climate-friendliness on their milk cartons. The same goes for the big players in the food industry with ambitious sustainability goals, who both Mootral and DSM see as potential customers. These companies will only become interested in a feed supplement if they can provide verified, publishable numbers for their sustainability reports or advertisements. The value of methane inhibitors is both material and semiotic, derived from the ruminal modifications it causes and the informational surplus it promises.

STS scholars maintain that ‘raw data is an oxymoron’ (Gitelman, 2013). Numbers are always already cooked or, maybe more to the point, ‘fermented’ by a series of distributed and often invisible actors and actants involved in data making. At one point in our interview, the carbon project manager at Mootral said, with a slight sigh of exhaustion: ‘Yeah, it’s cow burps. It’s about carbon, yeah, carbon metrics’ (Interview). In a way, this

expresses the slippery ontology of ‘carbon’ that has become an almost universal currency in climate policy and emissions trading to indicate the ecological impact of a series of different things, actions and processes. However, cow burps are not ‘carbon’ in and of themselves. Rather, a complex informational metabolism is necessary to turn cow burps into digestible carbon numbers. This becomes clear when considering the enormous effort taken to devise the methodology, get it approved and put it to use on the farm.

At first sight, the methodology is very similar to the protocols devised by the IPCC (2019) for the compilation of national emission inventories from livestock farming. The IPCC approach is about counting sheep (and of course cows) and multiplying these statistical population numbers by certain emission factors that specify the total emissions of a certain type of animal (sub)category over a year. What makes the Mootral methodology different is that it is specifically designed to take emissions reductions into account, which is not the focus of the IPCC accounting protocol. Generic emissions factor no longer suffice. Instead, it becomes necessary to directly measure how much methane a cow emits before and after receiving the feed supplement.

Measuring methane emissions of ruminants goes back to the early 20th century (Hammond et al., 2016: 16). The so-called respiration chamber, the oldest methane measuring apparatus, still serves as the ‘gold standard’ (Hammond et al., 2016: 26) due to its accuracy.¹⁰ However, it is very expensive and can only accommodate very few animals at a time, where they must remain for a couple of days. In recent years, a series of smaller sensing devices have become available. The SF₆ tracer technique equips the cow with a mouth gear and a canister on its back, automated head chambers and the so-called ‘sniffer’ technique measure methane on the spot while the animal eats or is milked. Hand-held laser devices detect the methane concentration of a cow burp when placed in front of the animal’s nostrils (Hammond et al., 2016: 23). The newer generation of sensing devices has made it much easier and less expensive to measure methane emissions and thus account for emissions reductions. Yet it still takes a lot of sensing, accounting and data work, as well as a dense ecology of experts (trained personal to conduct the measurements, and auditors to verify the results) to create carbon hoofprint numbers.

Curiously, the hand-held laser detector basically resorts to the same technology – infrared-absorption spectroscopy – that Carl Sagan’s imaginary Martians would use to detect life on Earth. The difference is, however, that the cow burp sensing devices are not used to look for indicators of life per se, but to track a particular form of life. Even when measuring the activities of the rumen, ‘carbon’ is essentially a ‘metric of the human’ (Whittington, 2016) focusing on ‘anthropogenic GHG emissions’. Searching for carbon traces in the dense web of relations down to the tiniest microbe, humans come to sense their more-than-human symbiotic self. According to Margulis (1999: 113f.), ‘(p)roprioception, the sensing of self, probably is as old as self itself. I like to think that we people augment and continue to accelerate Gaia’s newfangled proprioceptor capability’. Does this mean that humans have evolved to be the ultimate consciousness, the cybernetic *Selbstbewusstsein* of the symbiotic planet, as Lenton and Latour (2018) seem to suggest with their notion of Gaia 2.0.? Or should we stick with Dorian Sagan’s (2013: 123) speculations on his father’s musings on cow fart-sensing Martians that maybe ‘the aliens have detected us but don’t want to come close for the fear of Earth’s smell’?

The spatial politics of symbiotic engineering

‘As a microbiologist’, a scientist working at Mootral told us, ‘you start at the very bottom of the kingdom of life and this gives you an enormous lever’ (Interview; authors’ translation). He was not the only scientist we encountered who is fascinated with the collapse of scales that goes along with interventions in the symbiotic relations between cows and microbes. In the projects we analyzed, the microbial realm frequently figured as the Archimedean point to raise the planet. To a certain degree, this vision is in fact already latent in Margulis’ concept of the symbiotic planet. Together with Dorian Sagan, she proclaimed that ‘Gaia holds important implications not only for understanding life’s past but for engineering its future’ (Sagan and Margulis, 1997: 146). Mootral and DSM, therefore, tap into the ‘regulatory properties of living beings’ (Sagan and Margulis, 1997: 147) circumscribed in the concept of the symbiotic planet. DSM believes that the molecule they invented – 3NOP – can change the ruminal metabolism to stop the release of methane molecules – CH₄ – into the atmosphere. Similarly, Mootral promises that ‘by turning switches on a molecular level, we can provoke significant changes on a large, global scale’ (Mootral, 2020). Symbiotic engineering relies on and invokes a fascinating spatial imaginary. However, this spatial framing tends to occlude and sidestep other important relations like the socio-technical networks of climate governance, biocapital and life sciences on which the promised planetary effects rely as well as the unequal socio-economic spaces of global food production and consumption.

Attempts to – as one researcher put it – ‘join the molecular level to the ecosystem, to the planet level’ (Interview) through symbiotic engineering are less smooth and straightforward than frequently presented by biotech companies and public statements of scientists. Symbiotic engineering of bovine holobionts only has planetary effects when these interventions become scalable, when they become global. This, in turn, implies that the inhibitors must work in different livestock farming ecologies, penetrate markets globally and result in emissions reductions verified in the global infrastructures of carbon accounting. The collapse of microbial and planetary scales hinges on complex socio-technical scalability work. The ‘enormous lever’ only works due to the leverage of capital and in alliance with the gears of technoscience and the lubricants of climate governance. Through the practices of symbiotic engineering, the ‘infrastructure of microbes’ (Lovelock, 2000: xix) that assemble the ‘symbiotic planet’ become increasingly enfolded with the socio-technical infrastructures that make things global. Accordingly, the engineering promise encapsulated within the spatial imaginary of the symbiotic planet becomes complicit with the capitalist aspiration to scale up.

The focus on the relation between the microbial and the planetary, the rumen and the atmosphere, differs a great deal from the problem spaces environmentalists and social justice activists envision when addressing the cow–climate change nexus. Their efforts have focused on issues like the massive land use problem associated with cattle farming. A report by the FAO in 2006 found that ‘livestock production accounts for 70% of all agricultural land and 30% of the land surface of the planet’ (FAO, 2006: xxi). The 2019 Amazon rainforest wildfires renewed global attention on this problem. Critical commentators were quick to identify the search for new pastures and cropland for livestock as the main reason for the demolition of the rainforest. The fires destroyed valuable rainforest

ecologies that nourish the lives of myriad species and the livelihoods of indigenous people, and also function as carbon sinks critical for the regulation of the climate. The land use of cattle farming unquestionably aggravates its carbon footprint and accounts for 9% of the emissions of the livestock sector (Gerber et al., 2013: xii). Land appropriation, the often violent and destructive seizure of land for cattle farming,¹¹ goes hand in hand with ‘air appropriation’ (Folkers, 2020), the colonization of the atmosphere with carbon emissions. Much more than a Brazilian problem, this conundrum is an outcome of uneven global food geographies. NGOs and environmental justice activists frequently stress that animal-based diets in Europe, North America and Japan can only be sustained by ‘ghost acres’ or ‘virtual land’ outside these territories.¹² These countries, thus, effectively ‘import’, or rather colonize, land either by buying meat and dairy products or by buying feed crops produced in other parts of the world, especially in Latin America.¹³

These problematizations highlight the complex set of atmospheric, biospheric and socio-economic environments connected to cattle farming. By contrast, symbiotic engineering shifts the spatial scenery of intervention: from cattle in the environment to the environment within the cow, or, to be more precise, in the cow’s rumen. This spatial shift implies a shift in the problem to be addressed: from excessive meat consumption to excessive microbial methane production. Suddenly methanogens become the climate villains. Through this shift, symbiotic engineering backgrounds a series of social, ecological, and economic relations while foregrounding other, symbiotic entanglements from the microbial to the planetary scale. It is not about the relations between burgers and burning rainforests, imperial western lifestyles and indigenous livelihoods, but about the relations between the rumen and the atmosphere. It establishes a wormhole cutting through the dense and intricate topology of neo-colonial power relations, social injustice and ecological destructiveness associated with cattle farming and excessive beef consumption to establish a smooth link between microbial metabolism and the molecular composition of the atmosphere. Symbiotic engineering is clearly a *technical fix* that offers a technical solution to a complex socio-ecological problem. It is also a *spatial fix* in Harvey’s (2001) sense because it discloses the rumen as a new frontier of capitalist expansion to fix the (ecological) crisis of capitalism. Furthermore, seen as a biopolitical strategy, it introduces a *spatial shift* by focusing on certain spatial relations at the expense of others. Symbiotic engineering hides the reasons that made it necessary in the first place.

Some actors with whom we spoke were aware of some of the wider socio-ecological problems of cattle farming. They were very keen to point out that the feed supplements may – at least incrementally – reduce the need for animal food and thus for new cropland. Methane inhibition does not enact the uneven and destructive geographies of cattle farming. However, it does not counteract them either. It relies on and caters to current trends in livestock farming, such as making cows more efficient. By offering a simple and ‘efficient’ fix for ruminant methane emissions, it might enable the continuation of bovine business as usual in a carbon-constrained world. Methane inhibition is, therefore, what Goldstein (2018: 17–36) calls a ‘non-disruptive disruption’: A technological innovation that allows maintaining the socio-economic *status quo*. It seeks to remake the microbial metabolism without disrupting the cow’s digestion or the metabolic relations between cows and people.

How can we, in the light of this critique, understand the fascination among STS scholars with the topology of Gaia and for the symbiotic planet? The concept of the symbiotic planet is indeed good to think with, as it provides crucial insights for mapping the operating spaces of symbiopolitics. However, it is necessary to acknowledge and analyze how technoscientific and economic projects strategically make use of the ‘Gaian ontology’ (Lorimer, 2020: 6) and topology. Just celebrating the ramified and folded topologies of the symbiotic planet risks repeating the spatial imaginaries and occlusions of symbiotic engineering practices. Instead, it is necessary to critically analyze the work that goes into making things scalable and to look for the omissions of the Gaian imaginaries to provide a fuller understanding of the spatial logic of contemporary symbiopolitics. This is not to say that symbiopolitics is necessarily problematic. Other forms of ‘symbiosociality’ (Folkers and Opitz, 2020) are possible.¹⁴ But symbiopolitics is never innocent. After all, it is about metabolic relations that involve digestion and colonization, eating and being eaten, mutualism and parasitism. The analysis of symbiopolitics needs to ‘stay with the trouble’ (Haraway, 2016: 30). The search for alternative articulations of symbiopolitics, the strive to make good symbiosocial relations, therefore necessarily involves a critical reflection on current and emerging modes of symbiotic engineering.

Conclusion

In this article, we have analyzed attempts to reduce methane emissions through interventions in the symbiotic relations between ruminal microbes and cows. We see these interventions as symbiotic engineering, understood as a biopolitical technology that does not primarily address particular individuals or homogenous populations but focuses on holobionts and becomes effective by working on interlaced and convoluted sets of living things. In contrast to the proliferating symbiotic theory in the social sciences and the humanities, we understand symbiosis as more than a (normatively loaded) concept to rethink multispecies entanglements. Rather, we showed how symbiosis becomes a new field of technoscientific intervention and a capitalist frontier. Particular attention was given to the spatial operations and imaginaries of symbiopolitics, in this context. Symbiotic engineering seeks to ripple through interwoven ‘bodies tumbled into bodies’ (Gan et al., 2017) and their environmental envelopes. In the cases analyzed, symbiotic engineering targets methanogenic archaea to modify the ruminal microbiome, so that cows emit less methane in order to mitigate global heating. Symbiopolitics, thus, aims at far-reaching interdependent and inter-scalar processes, connecting molecular biopolitics to microbiopolitics, and bovine biopolitics to the politics of climate change.

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Notes

1. In this research we analyzed numerous scientific publications on ruminal metabolism, methane emissions and relevant mitigation strategies, as well as grey literature by international organizations and the involved companies. We conducted nine semi-structured interviews with scientists (both from the involved companies as well as collaborates from public research institutions) that have contributed to the projects as well as a business official and the carbon project manager at Mootral.
2. Foucault (1990: 139) famously singled out two poles of biopower, the ‘anatomy-politics of the ... body’ and the ‘biopolitics of the population’. His later considerations on the ‘milieu’ (Foucault, 2007: 17–23) implicitly introduced of a third, environmental, pole of biopower.
3. The concept of the holobiont, usually traced back to Lynn Margulis’s work in the 1990s, actually goes back to the German biologist Adolf Meyer-Abich who already introduced the concept in 1943 (Baedke et al., 2020).
4. Lorimer and Driessen (2013) introduce the concept of ‘bovine biopolitics’ and map four different modes of such a biopolitics, focusing respectively on agriculture, animal welfare, conservation and biosecurity. We argue that ‘climate’ needs to be added to the list. For work on the relation between cattle and climate change see McGregor and Houston (2018), Cooper (2017), and Ormond (2020).
5. On the etymological and genealogical relations between cattle and capital, as well as live-stock and stock markets, see Franklin (2007: 46–72).
6. For the distinction between appropriation and exploitation see Moore (2015). Cooper (2017) has rightly characterized the manipulation of cattle rumen as a real subsumption of nature. Marx’s (1968) distinction between formal and real subsumption is conceptually very close to Moore’s distinction between appropriation and exploitation.
7. Rose (2007: 4) stresses that molecular biopolitics goes along with the idea that ‘at the molecular level ... life can now be engineered’. However, we argue that molecular biopolitics is not exhausted by the focus on human genes as Rose suggests. Rather, as Braun (2007: 7) maintains, the engineering of life takes place ‘within wider molecular fields’.
8. Tsing (2012) therefore contrasts Matsutake mushroom, that lives in symbiosis with pine trees and cannot be cultivated, with sugar cane, that can be easily transplanted and made scalable. In contrast, however, we do not regard symbiosis and scalability as being incompatible but rather show what goes into making symbiotic changes scalable. For a recent take on scalability in innovation and public policy see: Pfothenhauer et al. (2022)
9. In this regard, Haraway seems to agree with Deleuze and Guattari, who also regard symbiosis as a mode of becoming. ‘Becoming ... concerns alliance. If evolution includes any veritable becomings, it is in the domain of symbioses that bring into play beings of totally different scales and kingdoms, with no possible filiation’ (Deleuze and Guattari, 1987: 238).
10. The basic principle for respiration chambers can be meaningfully traced back to the experiments on respiration and metabolism that Antoine Lavoisier and Armand Seguin conducted in

- the late 18th century to measure the transformation of *air vital* (oxygen) into carbon dioxide through the respiration of guinea pigs and humans (Beretta, 2012; Orland, 2016).
11. Land appropriation for livestock farming is, of course, not a new phenomenon. Karl Marx (1968) famously showed how the British enclosure movement dispossessed Irish and Scottish farmers at the expense of grazing sheep that supplied the emerging textile industry with wool. The import of cattle to the Americas followed the rising demand for beef in Europe and went along with a combination of ecocide (of the American buffalo) and genocide (of the indigenous population) especially in the US west (Rifkin, 1992: 40–109). On the relation between cattle and colonialism see also Ficek (2019).
 12. Kenneth Pomeranz (2000) has famously used the concept of the ghost acre to make visible the importance of colonial resource streams for the emergence of European industrial capitalism in the 19th century. However, the concept itself was introduced in the 1960s by the Swedish biologist Georg Borgstrom (1965) in his book *The Hungry Planet*. Here the ghost acre is closely associated with the excessive land-use of animal-based diets in rich countries. Today there are a series of concepts ('ecological footprint', 'land footprint', 'embedded land', 'virtual land') that similarly use land as the unit to account for the ecological impact of different socio-economic entities. For an overview see Mcmanus and Haughton (2006).
 13. A study by the German branch of the World Wildlife Foundation (2014) estimates that the EU resorts to thirty million hectares of ghost acres or what the authors call 'virtual land'. Soy imports predominantly (79%) used as feed for farm animals account for 50% of this land import with Brasil and Argentina as the most important soy importers. In addition, EU countries import significant amounts of beef from Latin America. The land footprint of beef is about three times higher than that of pork and chicken. One kilogram of beef consumes 27 to 49 square meters.
 14. Daniel Münster (2017), for example, shows how zero-budget farmers in India make use of the intimate entanglements between cows and microbes by fermenting cow dung to produce a powerful natural fertilizer.

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